System Optimization for Time-of-Flight PET

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Outline:

- **PET Electronics Requirements**
- **PET Electronics Trends**
- **OpenPET Electronics**

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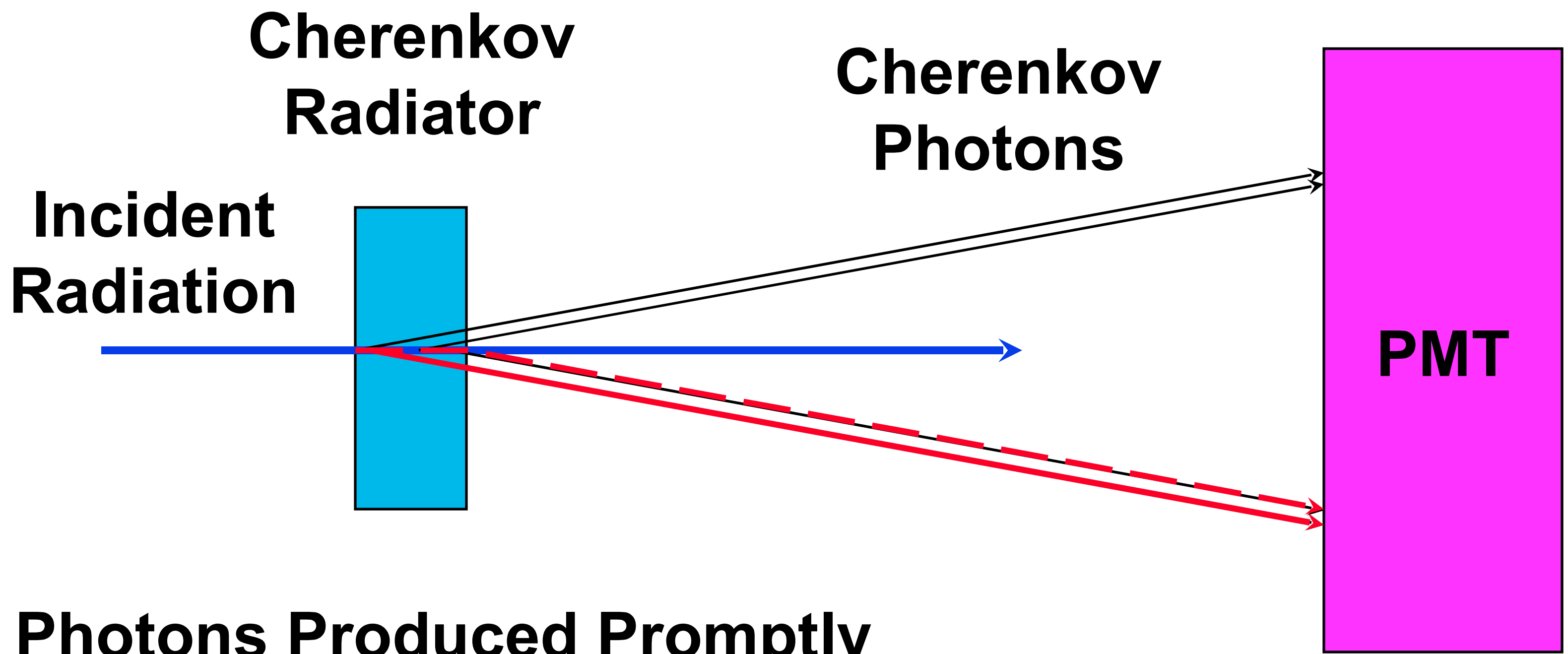
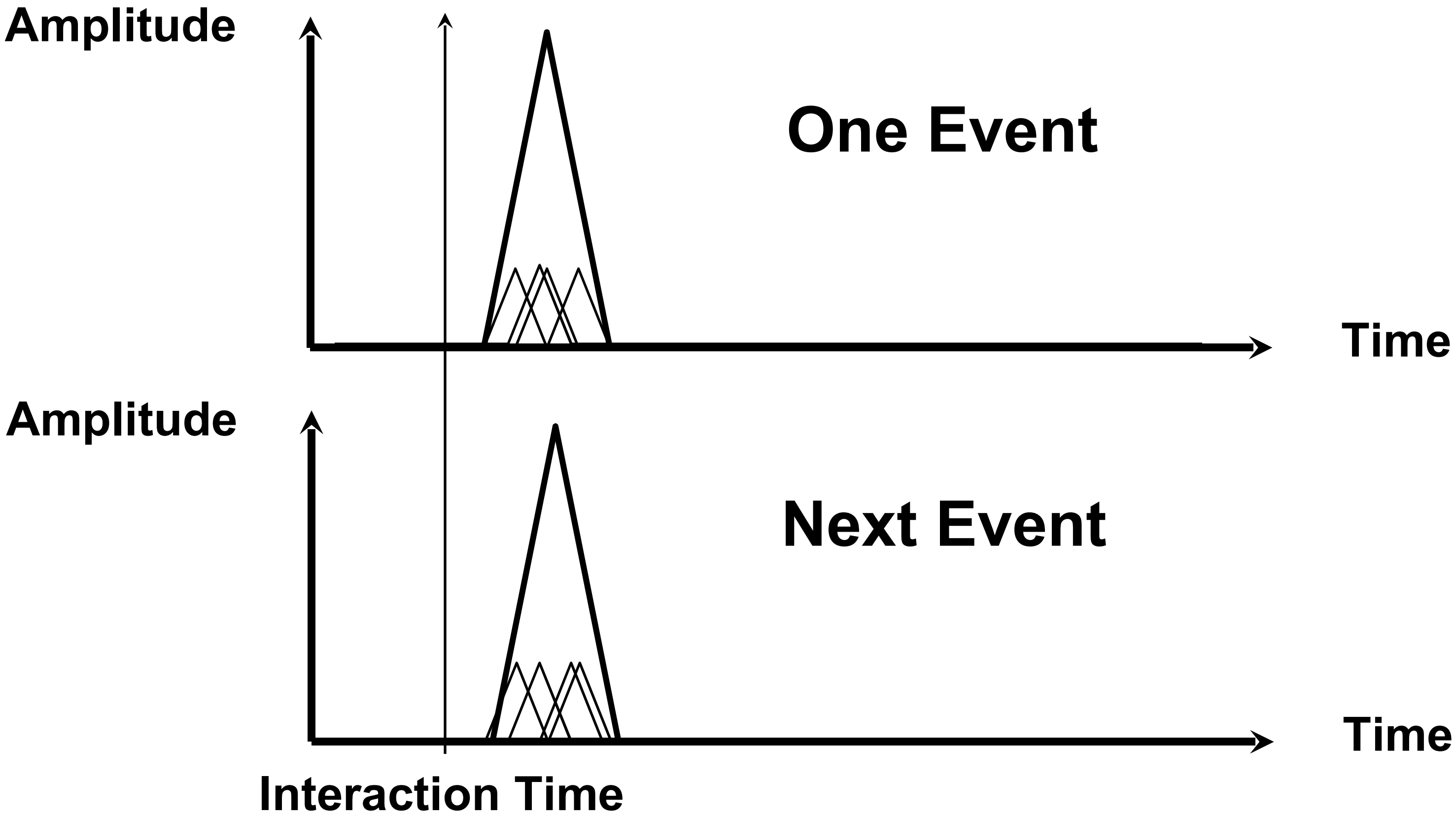
Time-of-Flight in HEP



- Photons Produced Promptly
- Photons Travel in ~Same Direction
- Small Time Variations due to Path Length Difference
- Small Variations due to Photon Production Position

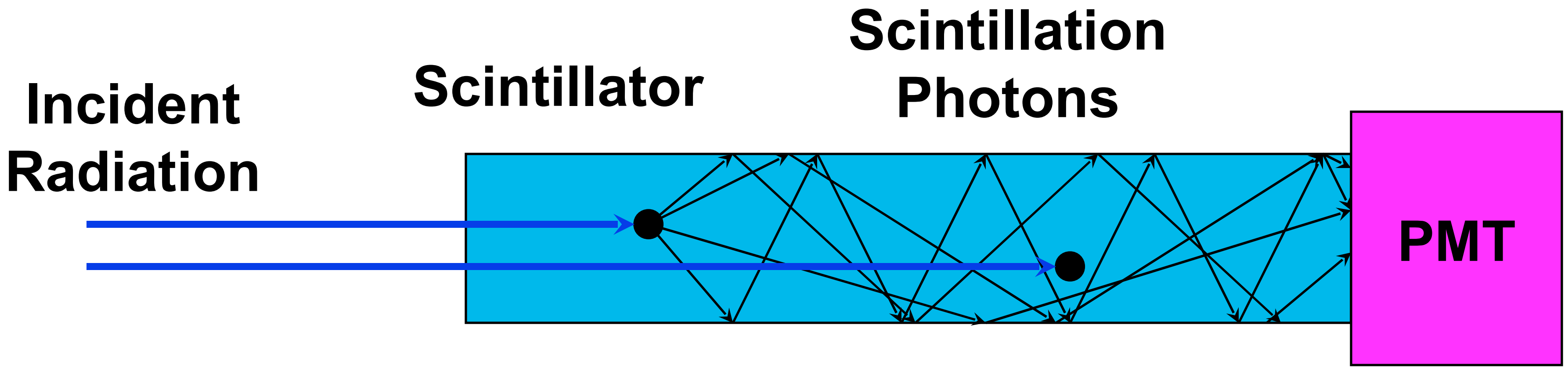
Time Spread Between Photons Arriving at PMT is Small

Arrival Time at PMT in HEP
(4 Photons Produced)



- Within Event, Photons Usually Overlap in Time
- Small Event-to-Event Variations

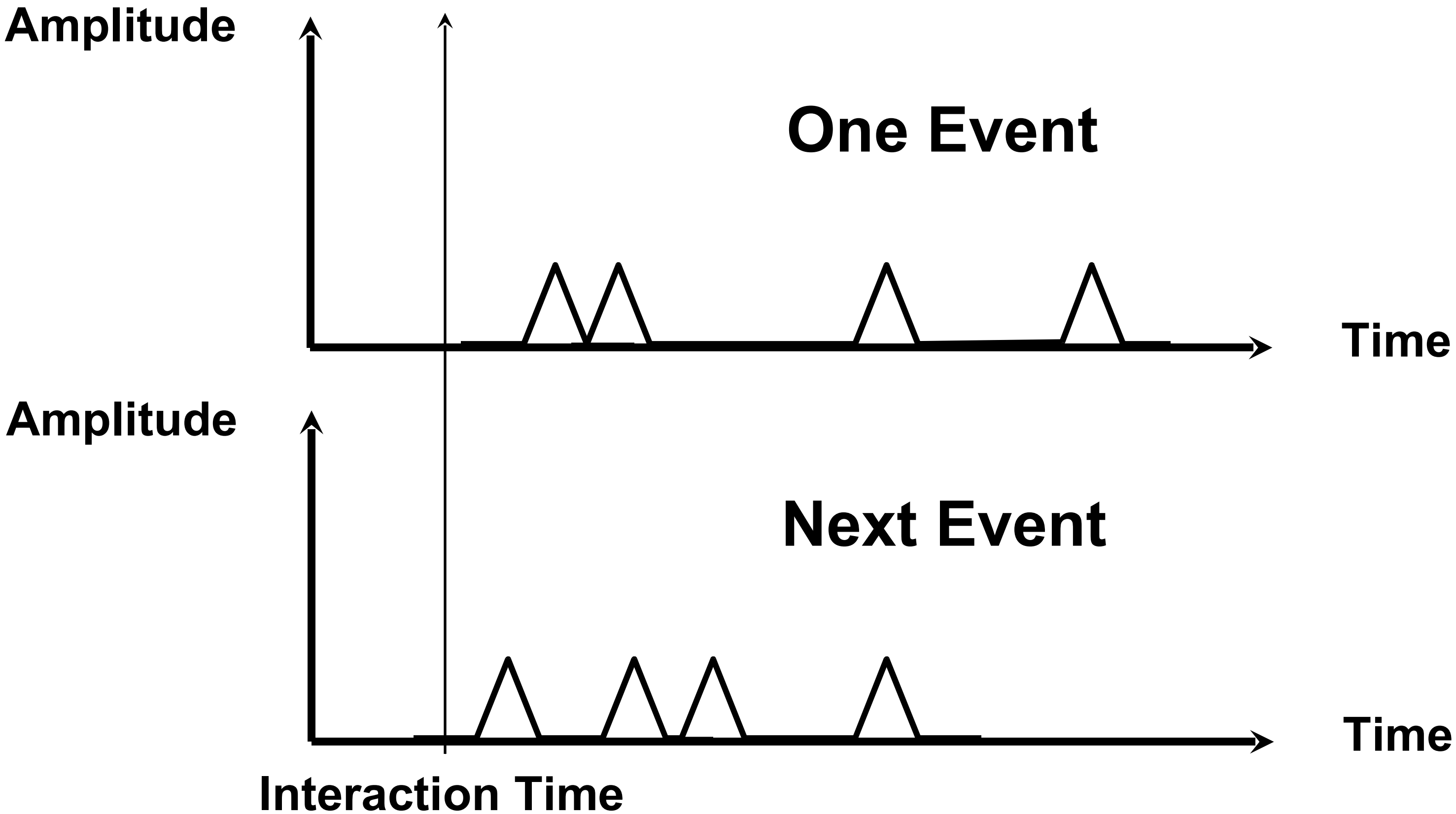
Time-of-Flight in PET



- Photons Produced w/ Scintillator Decay Time
- Photons Travel in All Directions
- Large Time Variations due to Path Length Difference
- Large Variations due to Photon Production Position

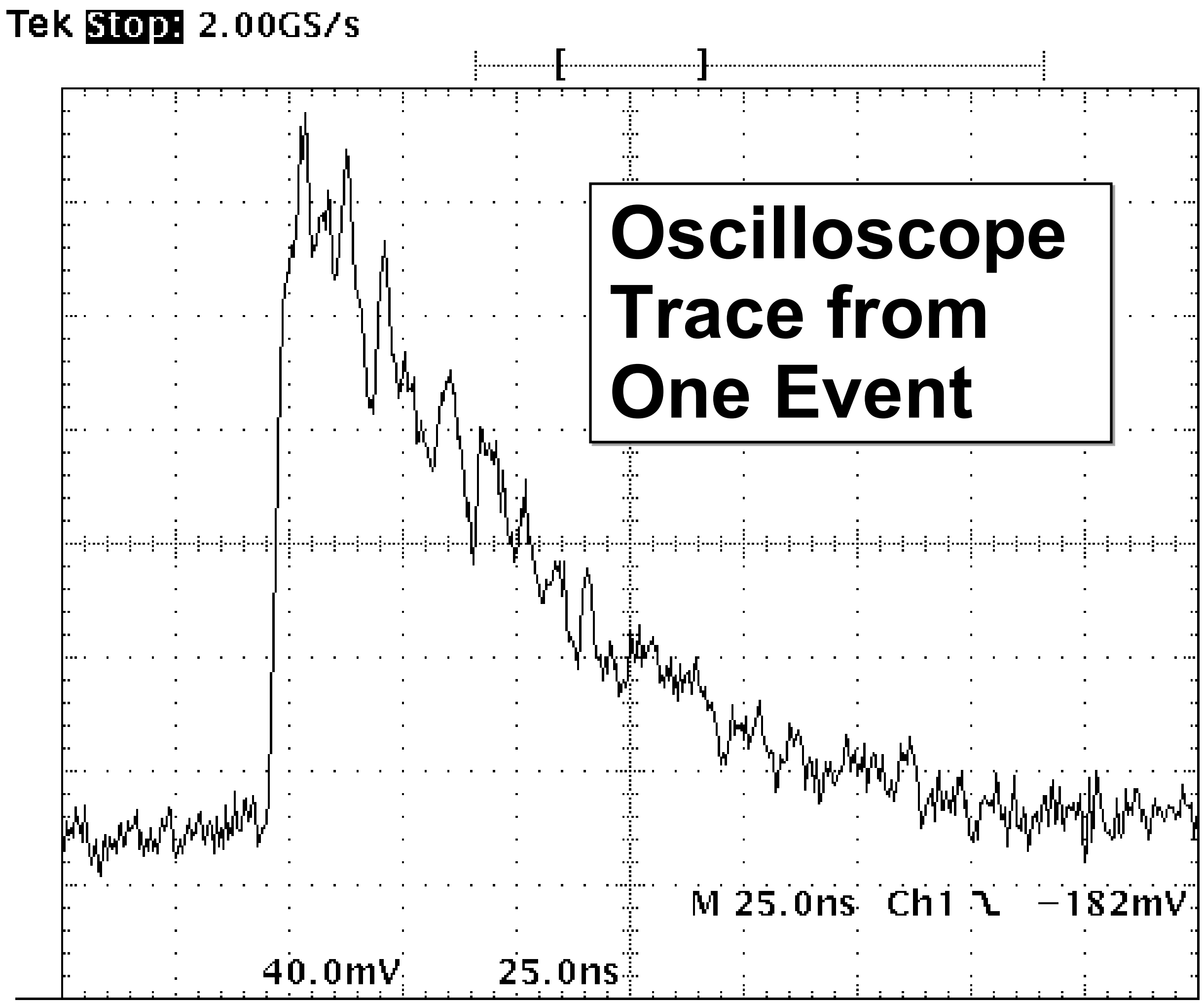
Time Spread Between Photons Arriving at PMT is Large

Arrival Time at PMT in PET
(4 Photons Produced)



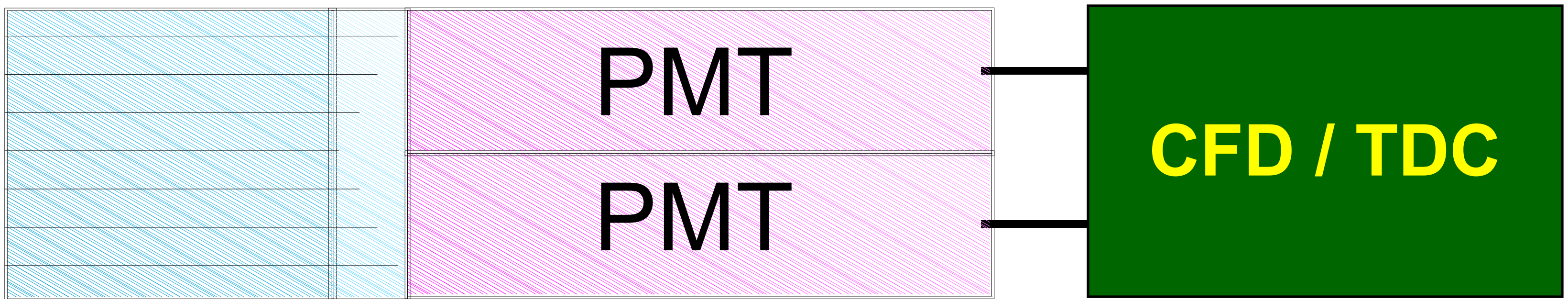
- Within Event, Photons Often Don't Overlap in Time
- Large Event-to-Event Variations

Why Good Timing Is Hard in PET



Statistical Fluctuations Make Accurate Timing Difficult!

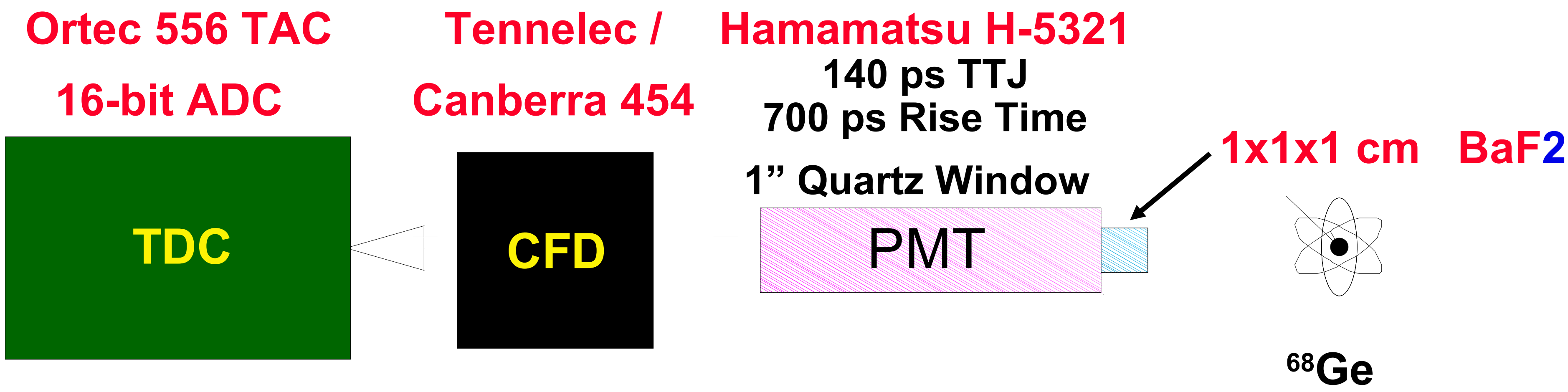
Measure Each Component in Timing Chain

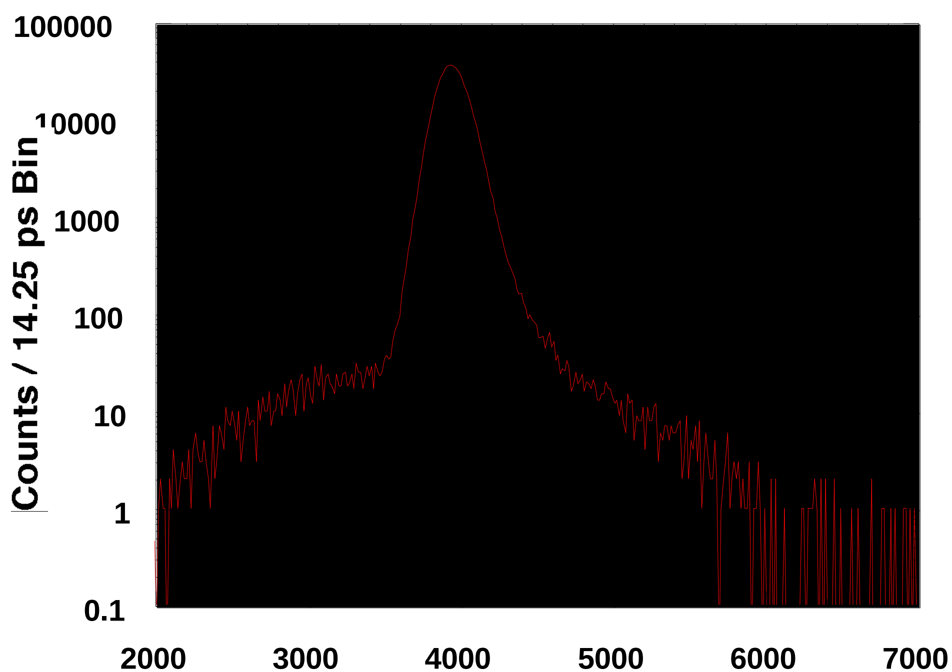


- Construct a Chain with "High Performance" Components
- Measure "High Performance" Timing Resolution
- Replace One of the "High Performance" Components with a "Production" Component
- Re-Measure Timing Resolution
- Difference (in Quadrature) is the Timing Contribution of the "Production" Component

Identify Where Can We Make Improvements

“Reference” Timing Signal





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“High Performance” Measurement

3x8x12 mm

LSO

Hamamatsu H-5321

140 ps TTJ

700 ps Rise Time

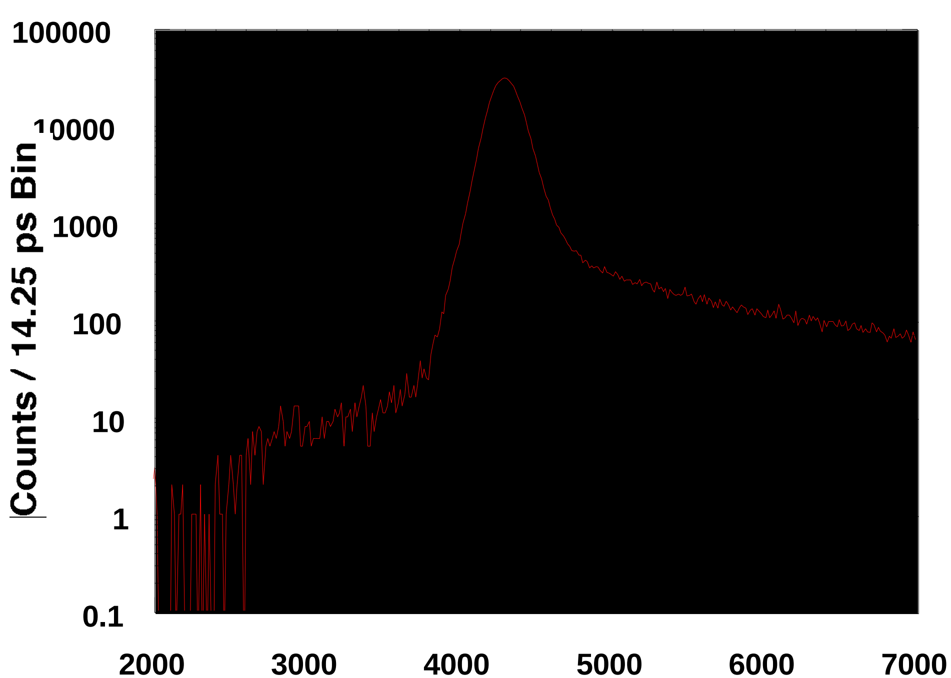
1” Quartz Window

Tennelec /

Canberra 454

Ortec 556 TAC

16-bit ADC



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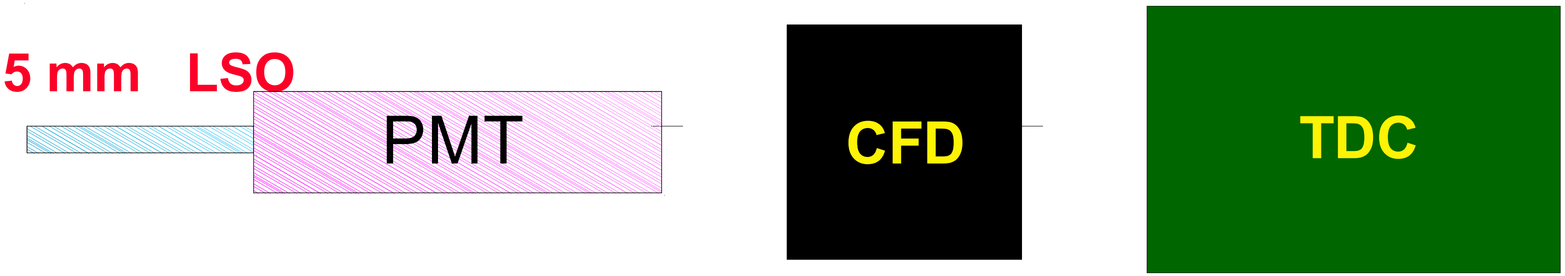
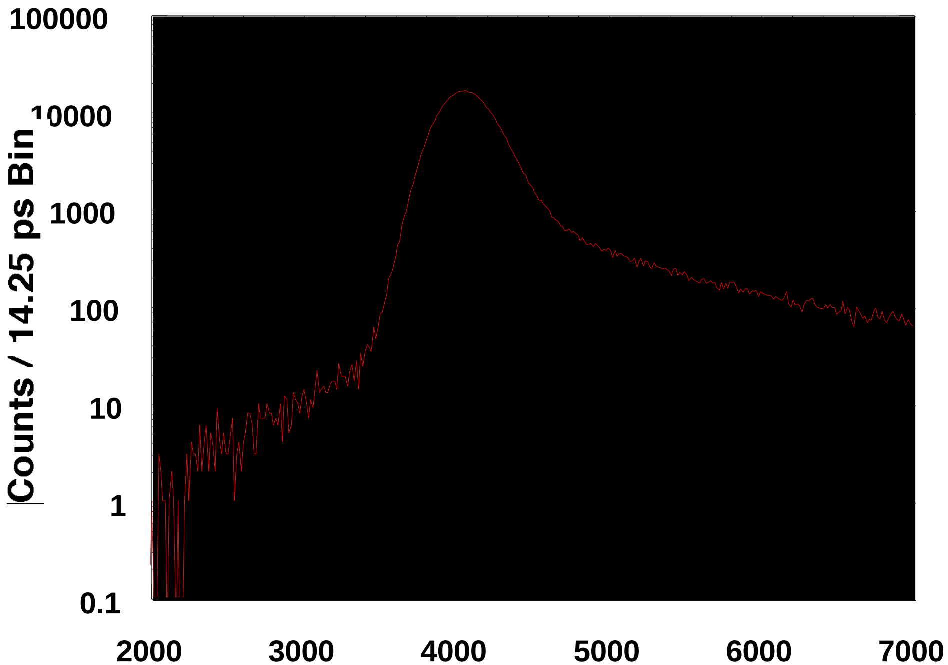
Scintillator Crystal

Hamamatsu H-5321 | Tennelec / Canberra 454 | Ortec 556 TAC 16-bit ADC

6.75 x 6.75 x 25 mm LSO





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394 ps – 221 ps ⇒

326 ps fwhm (batch 1)

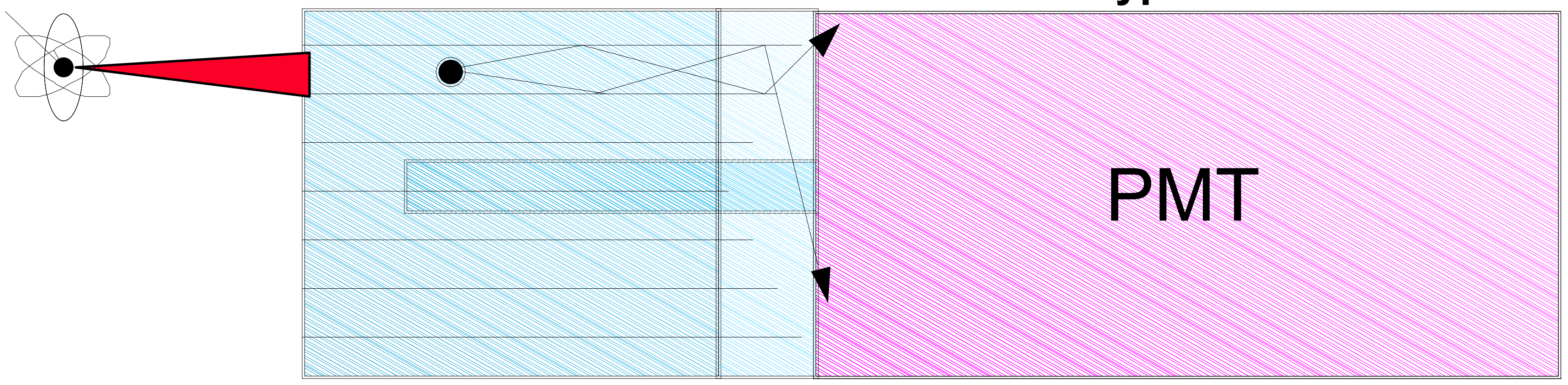
502 ps – 221 ps ⇒

451 ps fwhm (batch 2)

Scintillator "Block" Effects

CPS ACCEL V1 Block
8x8 Array
6.75 x 6.75 x 25 mm^3 LSO

Hamamatsu Fast 2" PMT
250 ps TTJ
1500 ps Rise Time
Prototype On Loan



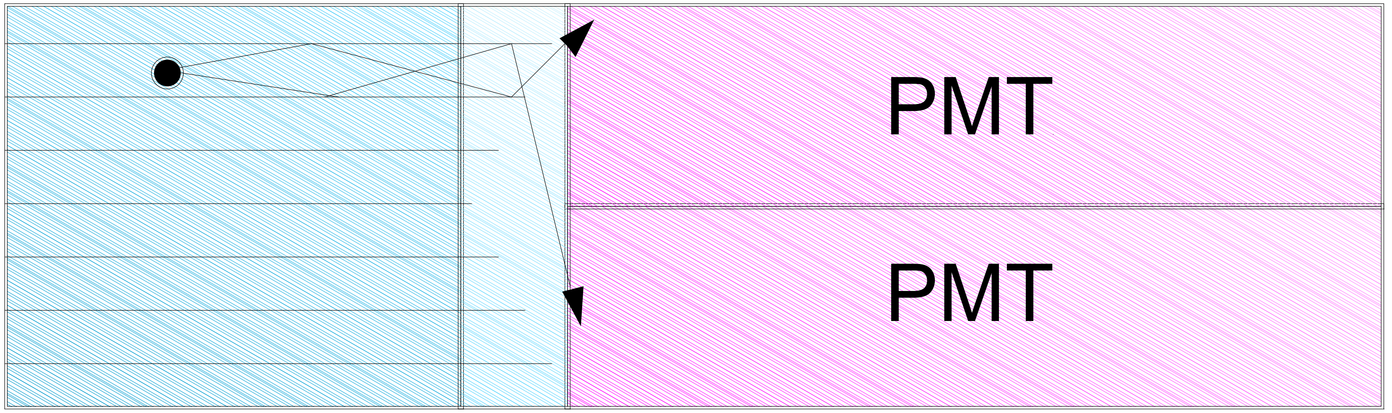
Configuration	Resolution
Single Crystal	355 ps
Block	577 ps
⇒ Block Contribution	454 ps

What Limits Timing Resolution?

Non-TOF Block Detector Module

Baseline
160 ps

Crystal Geometry
326 ps



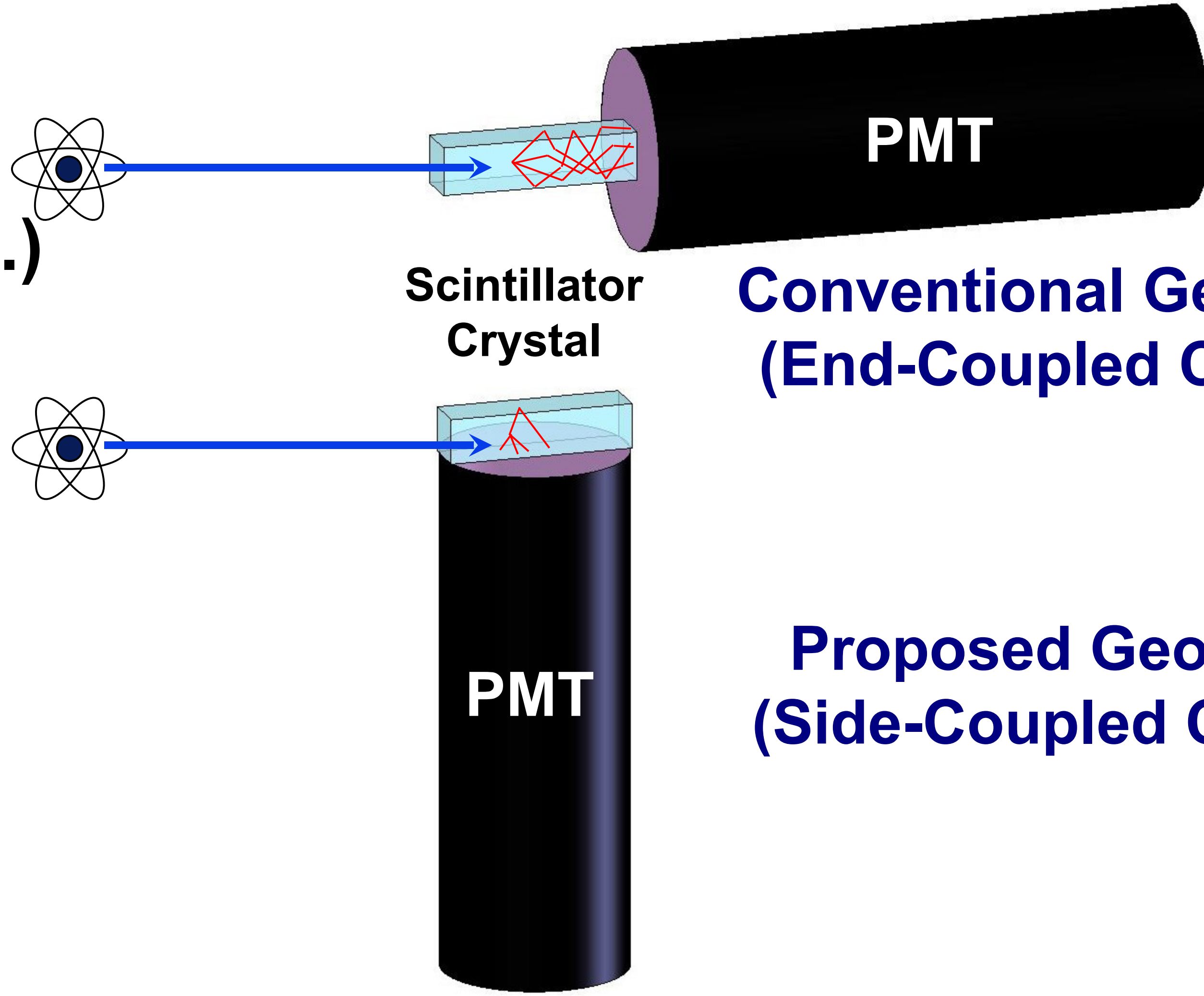
Light Sharing
454 ps

PMT
422 ps

PMT Array
274 ps

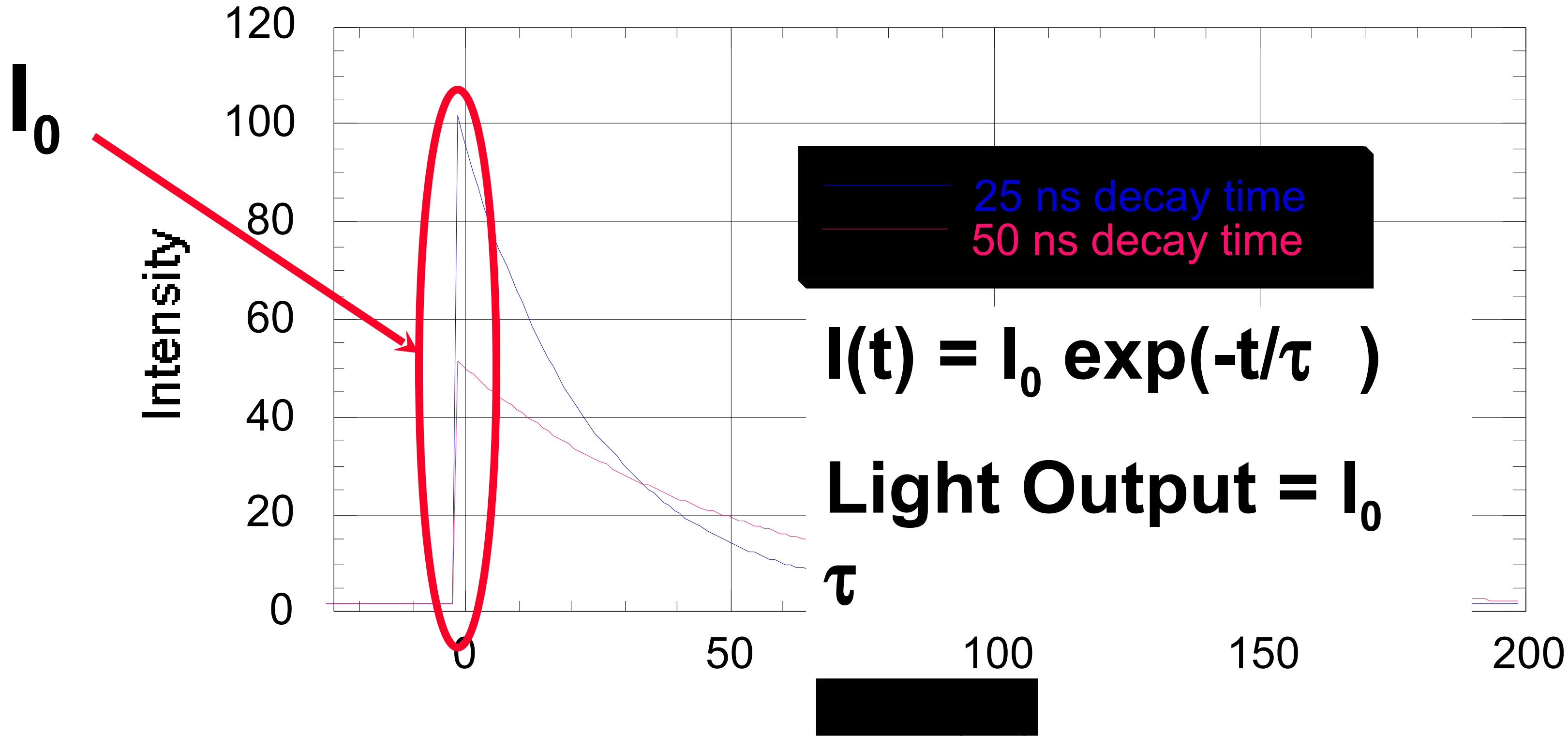
- **Many Factors**
- **“Optical Geometry” Particularly Important**

Proposed Side-Coupled Design



Shorter Optical Path Length & Fewer Reflections

Optimization: LSO Composition



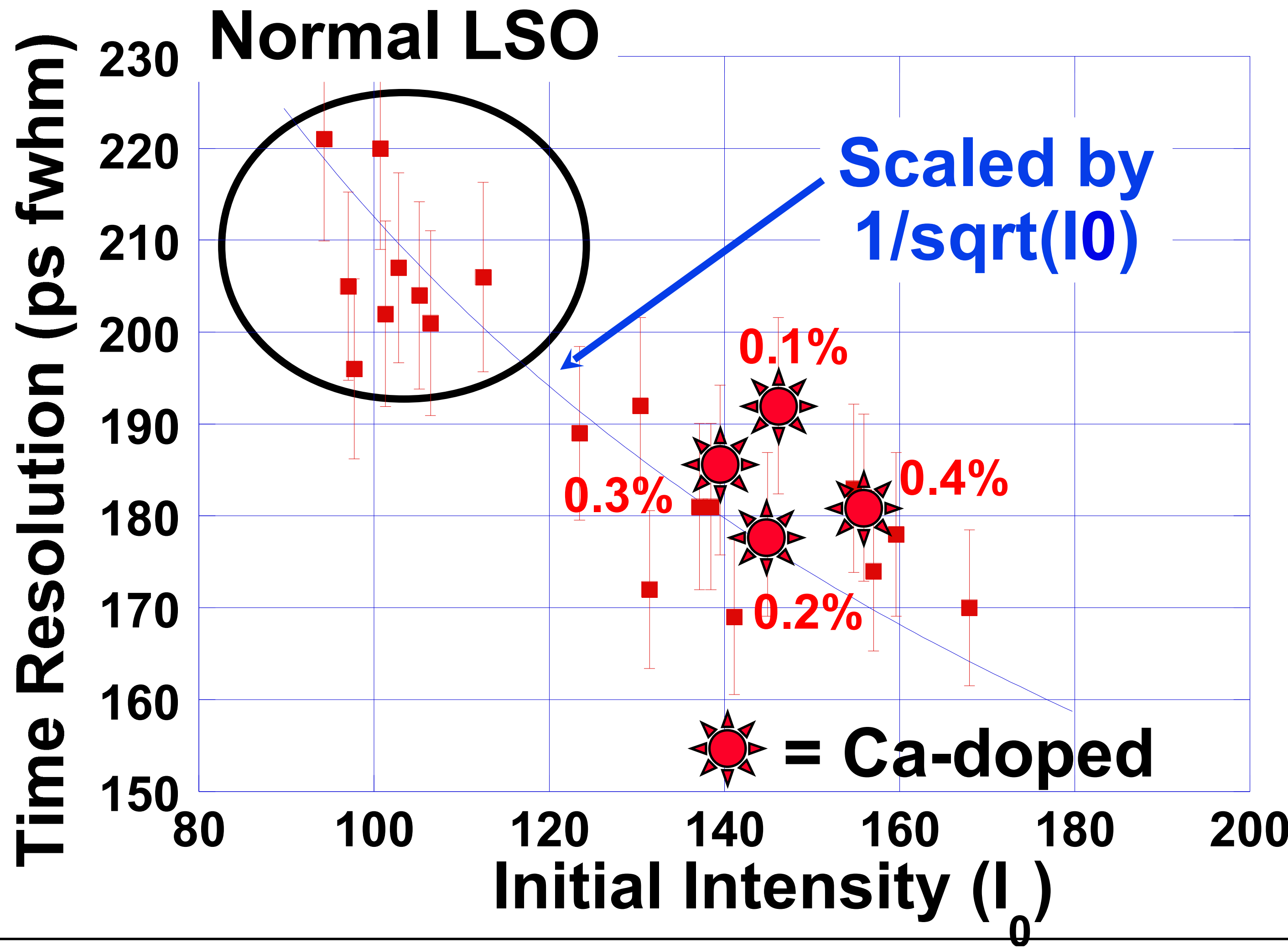
$I(t) = I_0 \exp(-t/\tau\ \ )$

Light Output = I_0 τ

- Both Scintillators Have Same Light Output (photons/MeV)
- Red Decay Time is 2x Longer Than Blue Decay Time

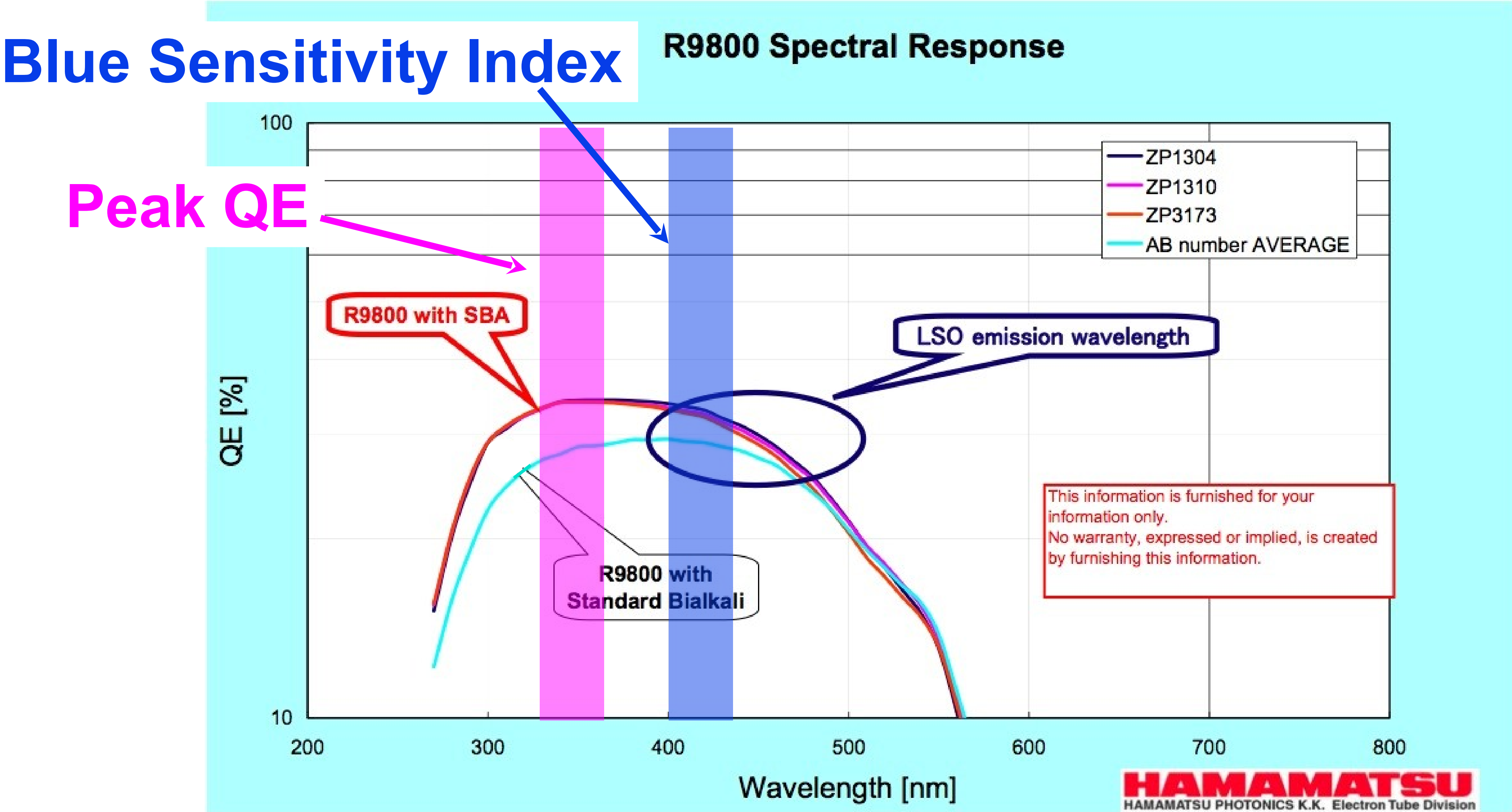
- Predicted Timing Resolution $\propto$ $1/\mathrm{sqrt}(I_0)$
- Want High Total Light Output & Short Decay Time
- Possible By Co-Doping LSO With Calcium

Optimization: LSO Composition



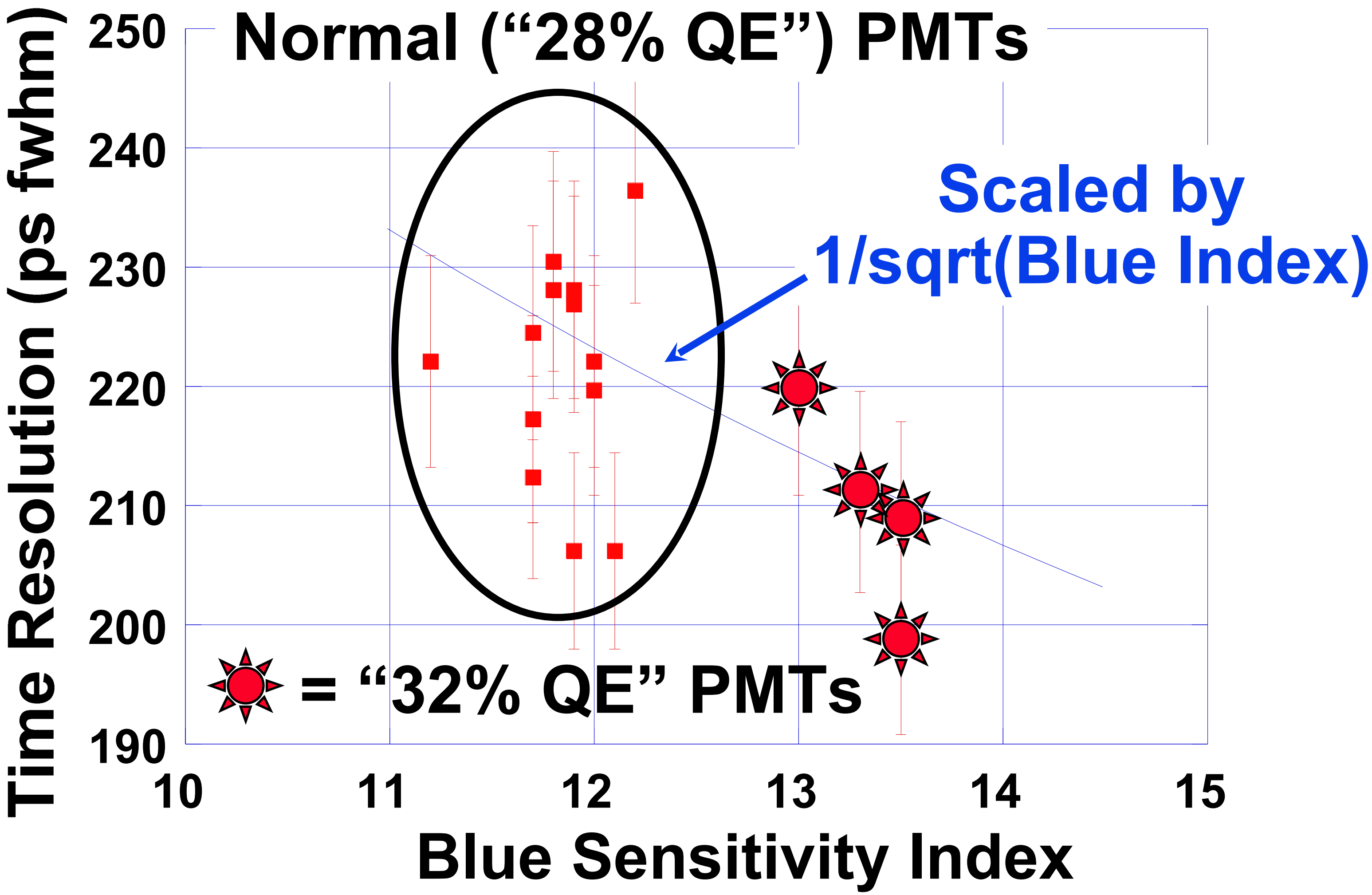
- Ca-Doping Gives Good Timing Resolution
- ~15% Improvement Over Normal LSO

Optimization: Photomultiplier Tube



- Predicted Timing Resolution $\propto$ 1/sqrt(QE)
- Want High Quantum Efficiency Version of PMT

Measured Results: High QE PMTs



- Increased QE Improves Timing Resolution by 7%
- Expect 10% Improvement with 35% SBA PMT

Summary

Hardware	Single (ps fwhm)	Coinc. (ps fwhm)	TOF Gain
End-Coupled Crystal	384	544	4.3
Side-Coupled Crystal	218	309	7.6
Co-Doped LSO	182	258	9.1
32% QE PMT	155	219	10.6
35% QE "SBA" PMT	148	209	11.1

- TOF PET with *Significantly* Better Timing is Possible
- To Achieve, We Must Optimize the *System*

TOF Gain for Whole-Body PET (35 cm)

Hardware	Δ t (ps)	TOF Gain
BGO Block Detector	3000	0.8
LSO Block (non-TOF)	1400	1.7
LSO Block (TOF)	550	4.2
$LaBr_3$ Block	350	6.7
LSO Single Crystal	210	11.1
LuI_3 Single Crystal	125	18.7
$LaBr_3$ Single Crystal	70	33.3

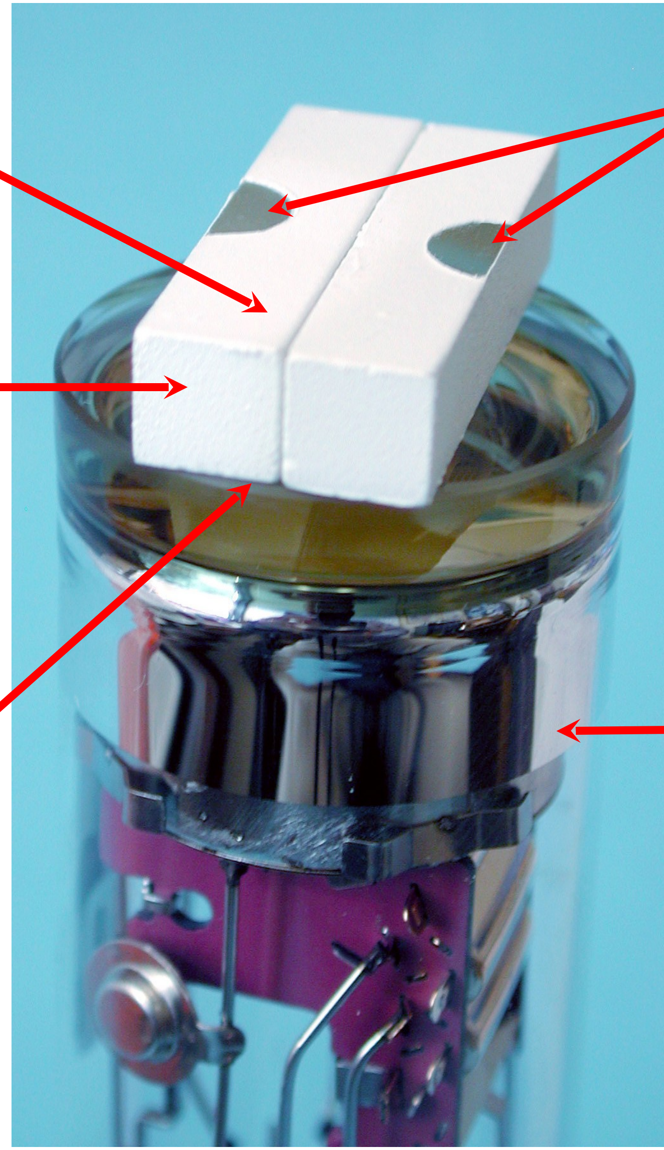
Incredible Gains Predicted…

Detector Module Design

Two LSO Crystals
(each 6.15 x 6.15 x 25 mm^3)

Reflector
(on all five faces of each crystal, including the face between the two crystals)

Optical Glue
(between lower crystal faces and PMT)



Hole in Reflector
On Top Face of Crystals

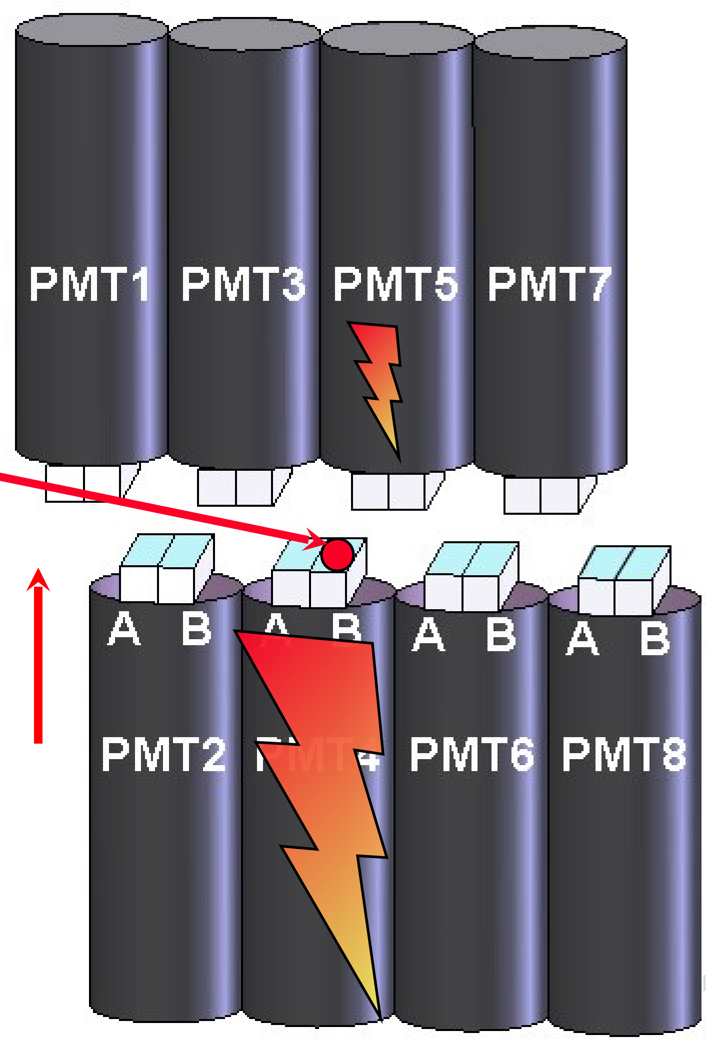
PMT
(Hamamatsu R-9800)

Two Side-Coupled Scintillator Crystals per PMT

Detector Ring Geometry

Crystal of Interaction

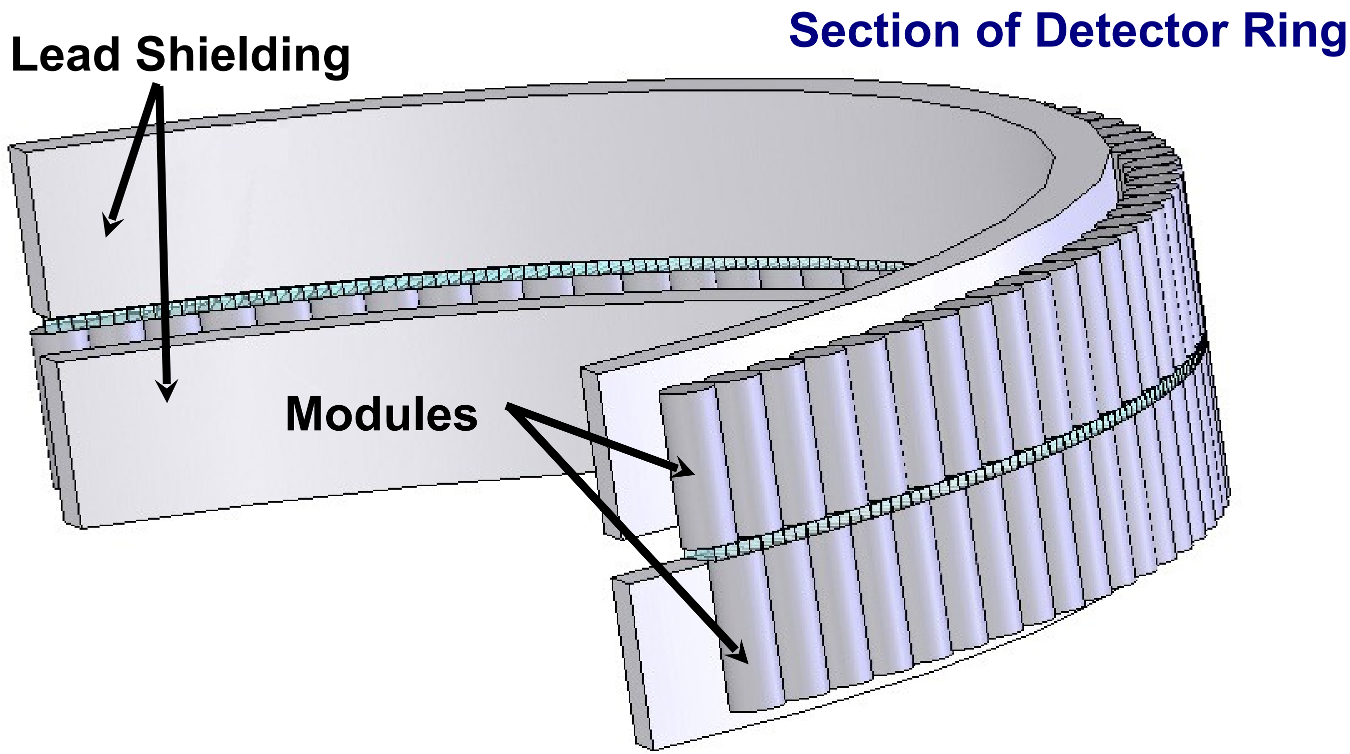
Exploded View



- Top face of each crystal (with hole in reflector) is coupled via a small (<1 mm) air gap to the edge of one opposing PMT.
- Light seen by the opposing PMT is used to decode the crystal of interaction.

Crystals Decoded by Opposing PMT

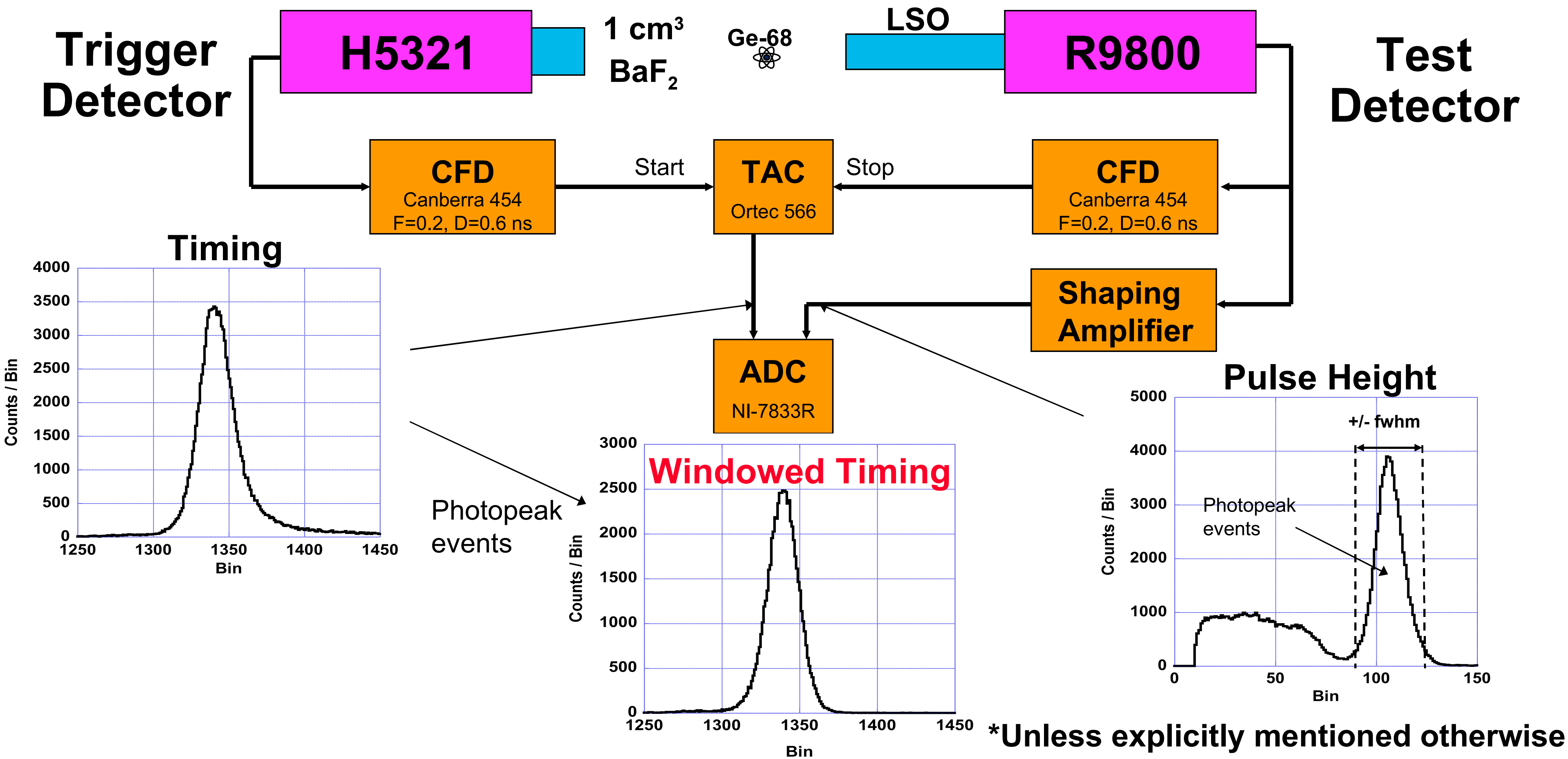
Camera Geometry



- Detector ring is 825 mm diameter, 6.15 mm axial
- 192 detector modules, 384 LSO scintillator crystals
- Adjustable gap (6 – 150 mm) between lead shields allows "scatter-free" and "3-D" shielding geometries

"Real" Single-Ring PET Camera for Humans & Phantoms

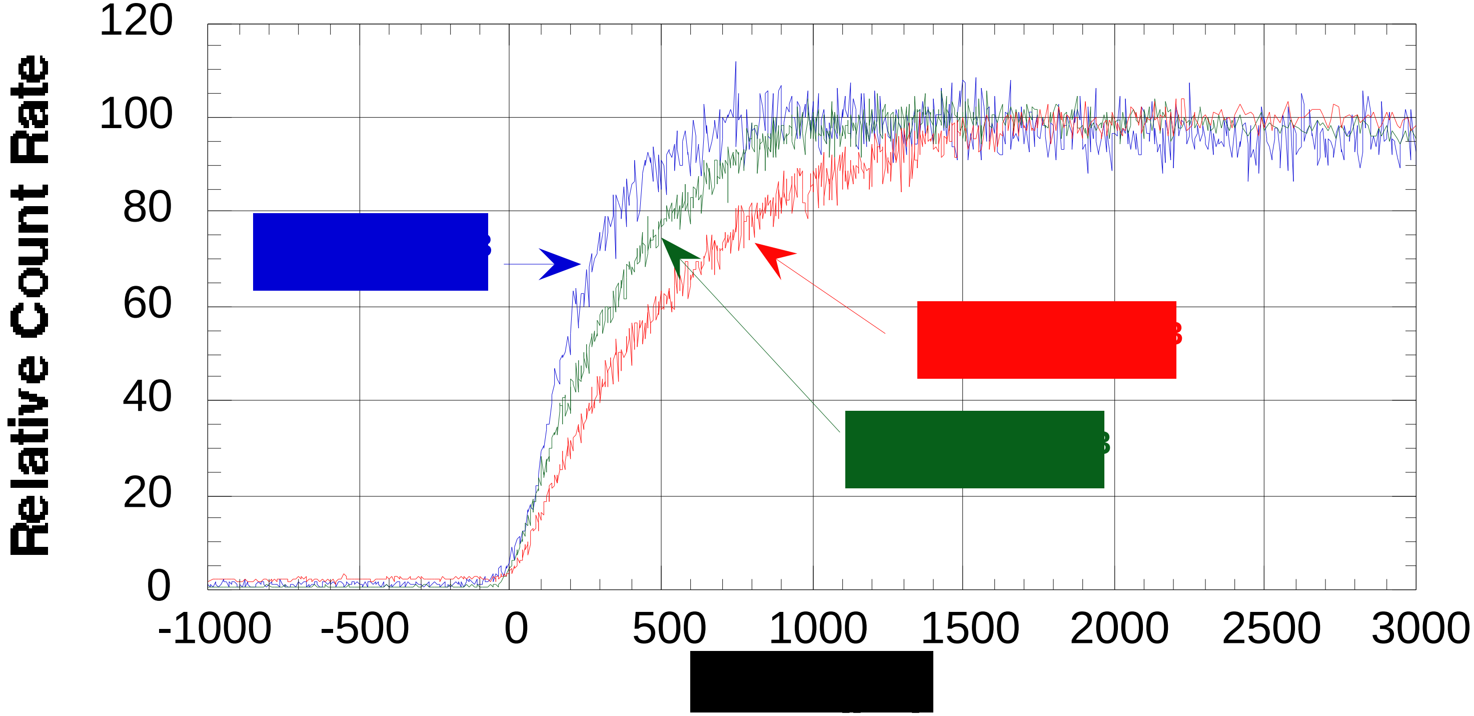
Timing Values will be for a *Single* Detector*



*Unless explicitly mentioned otherwise

- Only Accept Events in Photopeak Window
- Subtract (in Quadrature) 150 ps Trigger Contribution

Light Transport Affects Timing Resolution



Long, Thin Crystals Have Slower Rise Time